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Evaluating the new control structure for the promotion of grid connected photovoltaic systems in Spain: Performance analysis of the period 2008–2010

Jordi de la Hoz [a,*], Helena Martín [a], Jordi Ballart [a], Felipe Córcoles [a], Moisès Graells [b]

[a] Department of Electrical Engineering, Universitat Politècnica de Catalunya (UPC), Escola Universitària d'Enginyeria Tècnica Industrial de Barcelona (EUETIB), Carrer del Comte d'Urgell, 187, 08036 Barcelona, Spain
[b] Department of Chemical Engineering, Universitat Politècnica de Catalunya (UPC), Escola Universitària d'Enginyeria Tècnica Industrial de Barcelona (EUETIB), Carrer del Comte d'Urgell, 187, 08036 Barcelona, Spain

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ABSTRACT

This work presents public data collected from the Spanish Bulletin of the State (BOE), the National Energy Commission (CNE) and other Governmental agencies. Hence, the study describes the new regulatory scheme for grid connected photovoltaic systems (GCPVS) resulting after the Spanish PV power boom, the evolution of the sector, and analyses the control performance in terms of basic control theory principles, as proposed in the recent work by de la Hoz et al. (Promotion of grid-connected photovoltaic systems in Spain: Performance analysis of the period 1998–2008. Renewable and Sustainable Energy Reviews 2010;14(9): 2547–2563). Obviously, the object of study is too complex to be submitted to rigorous mathematical modelling, but the analogy presented provides useful tools for identifying and understanding the driving forces underlying in the evolution and regulation of the sector.

Contents

* Corresponding author. Tel.: +34 934 137 319; fax: +34 934 137 401.
E-mail address: jordi.de.la.hoz@upc.edu (J. de la Hoz).

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Acronyms

BOE	the Spanish Bulletin of the State
CNE	the National Energy Commission
GCPVS	grid connected photovoltaic systems
PV	photovoltaic
EU	the European Union
RES-E	electricity from renewable energy sources
FIT	feed-in tariff
RE	renewable energy
RD	Royal Decree
SR	Special Regime
RPA	the Pre-Allocation Register
MIMO	multiple-input multiple-output
SISO	single-input single-output
NREAPs	National Renewable Energy Action Plans
PER 2011–2020	Renewable Energies Plan 2011–2020
PANER 2011–2020	Spanish Renewable Energy Action Plan 2011–2020
RDL	Royal Decree Law
SES	Spanish Electricity Sector

Variables

k	GCPVS typology
i	number of the year
$Pb_{(k,i)}$	base power target for the GCPVS typology k assigned at the beginning of a year i [MW]
n	number of call for the year i ($n=1, 2, 3, 4$)
N	the number of annual calls ($N=4$)
$Cp_{(k,i,n)}$	power calls for the GCPVS typology k in the year i for the call n [MW]
$P_{\text{inv }(k,i,n)}$	the PV sector responds to $Cp_{(k,i,n)}$ by investing in a certain amount of PV power for the GCPVS typology k in the year i for the call n [MW]
$P_{\text{award }(k,i,n)}$	the PV power finally awarded for registration in the RPA for the GCPVS typology k in the year i for the call n [MW]
$P_{\text{installed }(k,i,n)}$	the installed power for the GCPVS typology k in the year i for the call n [MW]
$FIT_{(k,i,n)}$	the *FIT* value for the GCPVS typology k in the year i for the call n [c€/kW h]
$\text{Cost}_{(k,i,n)}$	the cost for every GCPVS type k, given a quarterly call n within a year i [M€]
$E_{(k,i,n)}$	generated energy by the GCPVS typology k, given a quarterly call n within a year i [kW h]
$T_{(k,i,n)}$	operating time done by the GCPVS typology k, given a quarterly call n within a year i [h]

1. Introduction

The recent evolution of the global photo-voltaic (PV) market reveals that the European Union (EU) has increasingly become a reference regarding the promotion of PV systems. According to the EPIA [1] in 2000 the global PV market achieved 280 MW (40.0% in Japan, 18.6% in the EU, and 8.6% in North America). Three years later, the 582 MW world-wide were contributed similarly by Japan and the EU (38.3% and 34.2%, respectively). From 2004 to 2010 the EU has been responsible for more than 60% of the global annual PV market (707 MW upon 13,246 MW in 2010).

These figures are due to the EU will and the EU policies aimed at promoting electricity from renewable energy sources (RES-E). Hence, the EU set energy targets for each of the member states [2,3] while encouraged their individual responsibility to develop the particular means to attain these goals. The analysis of the different strategies and tools adopted by the EU states has deserved a relevant interest in the literature [4–7]. Specifically regarding the promotion of PV systems there are some studies investigating the polices and instruments applied within the EU [8–13].

Data shows an exponential growth of global annual PV market in the EU during the period 2008–2010: 5130 MW in 2008, 5619 MW in 2009, and 13,246 in 2010 [1]. A deeper analysis of these data reveals that the states that most contributed to this progress were Germany, Spain and Italy, which adopted promotion policies based on the feed-in-tariff (*FIT*). Several works have addressed the performance analysis of the different *FIT* options employed [14–16] and the impact on the German [17,18] and Spanish sectors [12,19,20].

The review by Couture et al. [14] provides a detailed analysis of the different *FIT*s applied, examines advantages and drawbacks, and indicates the significant influence of Germany and Spain. In the case of Germany, the model adopted since 2000 has been (despite minor legal changes) a degressive *FIT* without limits on the installed power [14,17,18]. As a result, in the period 2006–2010 the German PV sector experienced annual growths from 40% to 75% (2899 MW, 4170 MW, 5979 MW, 9785 MW, and 17,193 MW installed cumulative PV power). Furthermore, Germany has attained the world's first position regarding installed cumulative PV power and has become a leading country regarding renewable energy (RE) research and industrial development [14,18]. On the other hand, the economic impact of such a promotion policy on consumers cannot be neglected [21].

Another significant case for studying the economic impact of RES-E promotion policies based on *FIT* is Spain, specifically the PV sector. In 2008, the *FIT*-based promotion policy in Spain achieved 2708 MW of newly installed PV power, 43% more than Germany [1], which totaled 3398 MW and gave Spain the second largest installed cumulative PV power, just behind Germany. Again, this sudden effect resulted in a promotion cost larger than initially expected [22].

Germany and Spain reacted in different ways to contain the cost of PV promotion. While Germany preserved the model and increased the tariff degression rates [14,18], Spain proposed by proposed Royal Decree (RD) 1578/2008 [23] a new model that combined *FIT* with new control mechanisms to reduce the economic impact. Since *FIT* mechanisms are still considered for RES-E promotion [14] and cost limitation is a concern [24], the study of the promotion policy in Spain, as well as in Germany or Italy, provides a valuable insight. In the case of Italy, a *FIT* policy similar to German model indicates again the importance of a correct control structure while designing the promotion mechanisms. The PV power installed in Italy in the years 2009–2011 was 717 MW, 2321 MW y 9000 MW, respectively. These 224% and 288% growths have also produced a significant economic impact [25].

The Spanish PV boom was recently analyzed under the perspective of control principles [26], which allowed identifying the elements in the promotion mechanisms that may cause instability and anticipate some undesired effects. The new promotion framework established by RD 1578/2008 after the Spanish PV boom may be regarded as a particular control mechanism

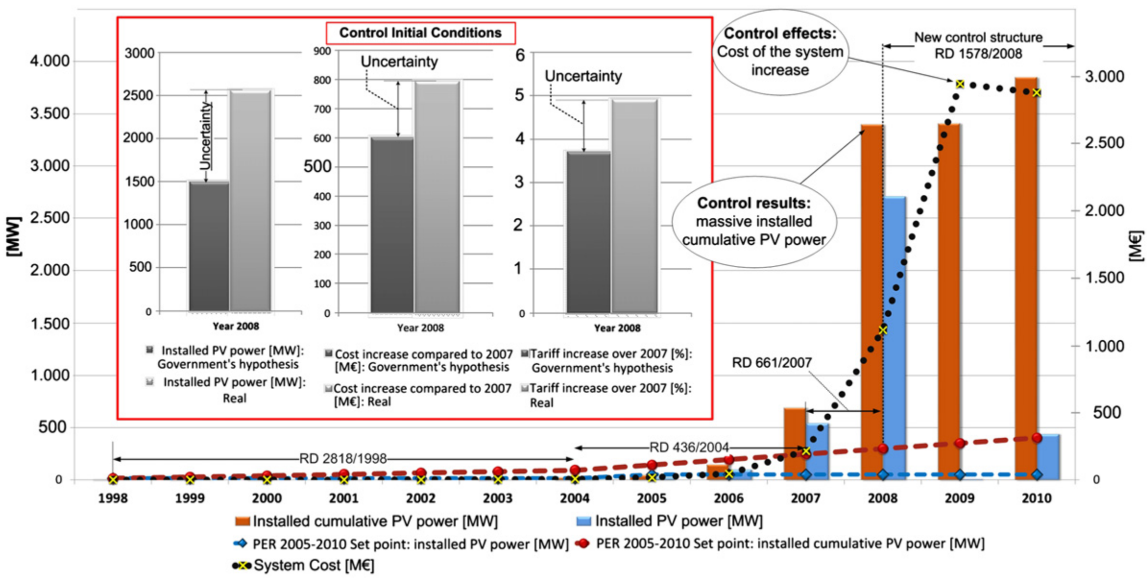


Fig. 1. Evolution of the cumulative power in the period 1998–2010 and economic impact. *Source*: self elaboration based on CNE and Ministry of Industry data.

conceived to adapt the remuneration once the energy targets have been largely exceeded. This new framework has been discussed by several authors [5,9,12,14,15,20,24,27,28] but to the authors knowledge its performance regarding the new energy targets has not been analyzed in terms of the control structure: advantages, drawbacks and outcomes.

Following the same approach [24,26] this paper first examines the new energy targets after the Spanish PV boom (Section 2). Next, the PV legal, economic and technical frameworks are analyzed and described in control terms by developing an analogy with control principles in order to provide tools for identifying and describing the elements that have ruled the system as well as the reasons for its use (Section 3).

Accordingly, based on public data available from the Spanish Bulletin of the State (BOE), the National Energy Commission (CNE), and other Governmental agencies, the effects of control actions on PV performance stemming from different legal and administrative decisions are presented and discussed (Section 4).

Finally, all the factors or change drivers deemed relevant for the evolution of the PV sector during the period of analysis are duly systematized and conclusions are raised (Section 5).

2. The situation after the Spanish "PV power boom"

In 2008, the new PV capacity installed worldwide reached 5580 MW; 45% of it had been installed in Spain, where the new PV capacity had raised from a trifling 26 MW in 2005 to an impressive 2708 MW [1].

Fig. 1 shows the evolution of the cumulative power in the period 1998–2008 – surpassing 3000 MW when the target for 2010 was 400 MW – and its consequent economic impact. In 2008, the governmental forecasts [22] stood at 600 M€ the increase in the cost of GCPVS premiums over the previous year, impacting with a 3.6% increase on the electricity tariff[1] . Nevertheless, final data set the premium additional cost in approximately 800 M€, equating to an increase around 4.9% on the electricity tariff.

The parallelism of the concepts between the legal framework governing the PV sector and a simple closed-loop control system that helps understanding the sector running out of control is given in Fig. 2a.

According to this approach, the PV power target represents the system input or set point, the PV power really attained is considered the system output, and the error signal is the difference between the set point and the actual system response. Also, the different laws enacted in order to reach the desired power target are regarded as the control block of the Spanish PV energy sector, which is the plant to be controlled.

This analogy provided useful tools for identifying the major shortcomings of the legal frameworks in force during the period 1998–2008, which ultimately led to the bull market that characterized the so-called Spanish PV power boom. These issues are the following:

a. Lack of differentiated PV power targets for on-roof GCPVS.
   This fact contributed to the poor implementation of on-roof GCPVS, as less than 10% of the PV installations in Spain were located on roof [26].
b. The definition of promotion mechanisms regarding two main aspects:
   i. The *FIT* and the power capacity of PV facilities:
      On-roof GCPVS were indirectly promoted by granting a higher relative reward to the facilities with lower production capacity, which were likely to be on-roof. However, large PV installations, mainly located on floor, could claim for the energy price initially conceived to promote small on-roof PV plants[2]. This ill-defined control law, relating the *FIT* to the rated power rather than to the type of facility, contributed to the failure of on-roof GCPVS promotion and to the lopsided development of the PV sector.
   ii. The *FIT* and the achievement of the objectives:
      The extent to which power objectives were met was not

[1] The electricity tariff can be divided into three different sections, namely, the cost of electrical energy production, the retailer's margin – in the event that energy is purchased through a representative – and the access tariff. The payment of premiums in the Special Regime (SR) – which includes GCPVS – is among the costs comprehended by the access tariff.

[2] This loophole allowed the segmentation of large facilities into smaller ones eligible for the highest *FIT*. Consequently, most of the large facilities were not registered as a unique facility but as multiple single installations, resulting in the so-called solar parks.

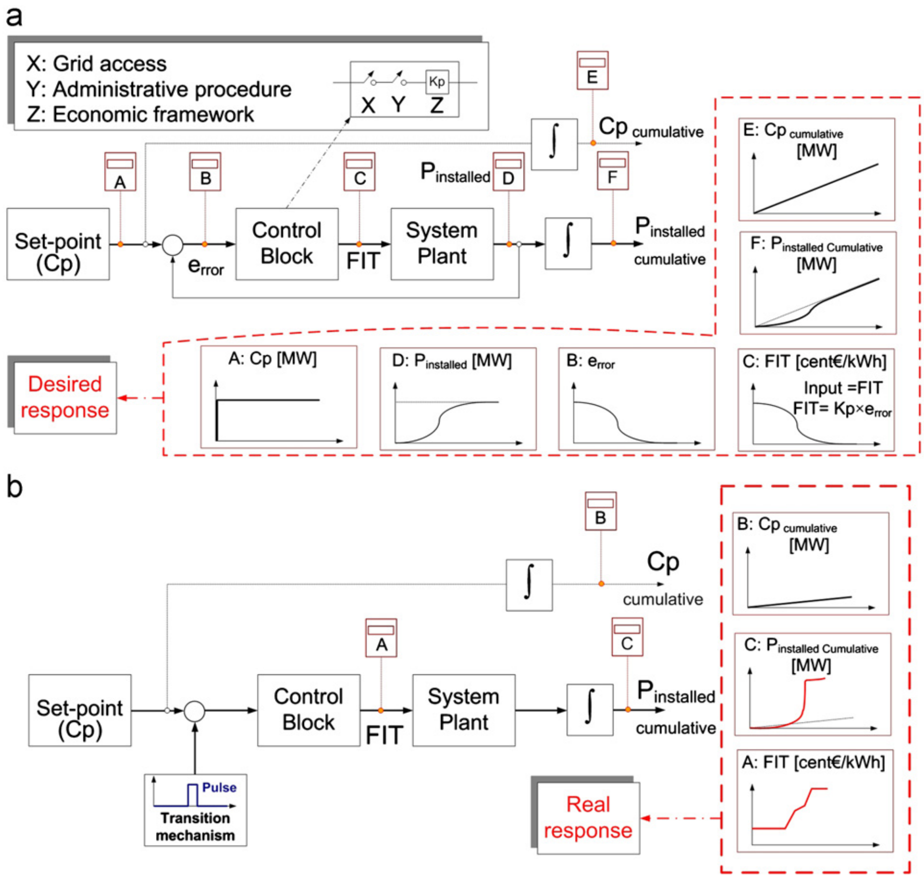


Fig. 2. Basic control system structure and former control system applied. *Source*: self elaboration.

used to modulate the *FIT*. Furthermore, as power results approached the target, the *FIT* was increased. In control terms, the control law was decoupled from the error signal so that the supposed closed-loop control structure ran open-loop, contributing to the unstable response of the system (Fig. 2b).

c. The transition mechanism, regarding two main aspects:
   i. The transition mechanism design:
   As the GCPVS objectives were about to be met and the overrated *FIT* was not yet necessary, a transition mechanism[3] was designed and implemented. Once 85% of the target was attained, this *FIT* value would be granted only for those facilities registering within one year. Thus, this mechanism stimulated the sector to engage as much capacity as possible before the favourable economic conditions ended (Fig. 2b).
   ii. The regulatory uncertainty after the completion of the transition period:
   The lack of timely information about the changes in the value of the tariff differential[4] introduced a great uncertainty. Besides, prior to the approval of the tariff differential, a retroactive and economically unaffordable retribution framework had previously been proposed by the government [29], which contributed to beef up this uncertainty[5].

Thus, the transition mechanism can be regarded as a pulse added to the system's set point as well as held responsible for its out-of-scale response. Given this situation, a new regulatory framework – RD 1578/2008 – was enacted in 2008 in order to stabilize the Spanish PV market. This new control architecture was aimed at:

a. The stability[6] of the system output.
b. The restriction of the economic impact of the new facilities[7].
c. The adjustment of the remuneration to the expected cost reduction of PV technology and to the achievement of the power objectives.
d. The effective promotion of GCPVS on roof.
e. The continued investment in PV technology.

3. The new control scheme for the PV sector

3.1. Stability: The basis of the new energy policy control

In the simple control structure shown in Fig. 2a, the system response relied solely on the design and tuning of the control block, which in practice was implemented as a simple gain constant *Kp*. Either the tuning of this simple controller, or a more

[3] RD 661/2007, article 22.
[4] A new economic framework was announced but not yet defined in RD 661/2007. It was known only two months ahead the end of the transition period.
[5] This first proposal was refused by the CNE in December 2007, due to its retroactive nature [29,30]. It can be regarded as an attempt to control the PV market during the transition period, and not after it.
[6] A system is stable if a bounded input produces a bounded output.
[7] While ultimately this objective was not explicitly defined in the RD 1578/2008, it was contained in the financial summary of the proposal of this Law [22]. A ceiling from 3.5% to 4.5% was established for the increase in the electricity tariff during the period 2009–2020.

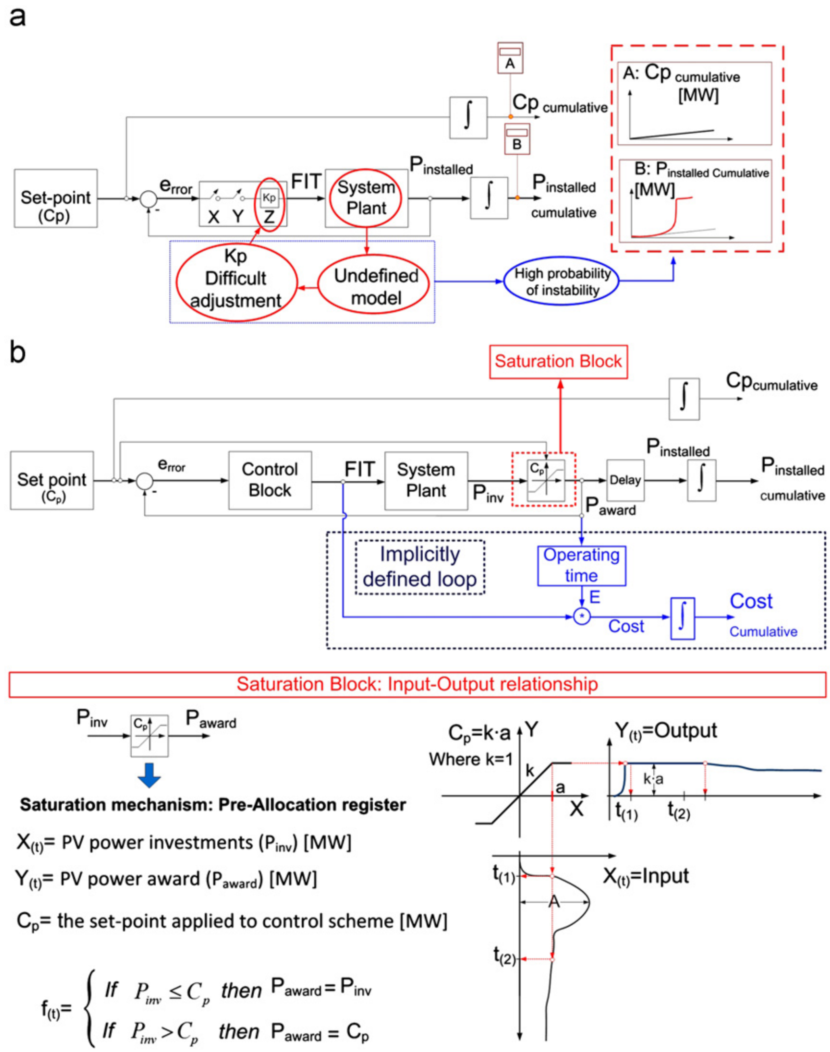


Fig. 3. Basic control system structure challenges and new control system conception. *Source*: self elaboration.

sophisticated one, would still face the following obstacles (see Fig. 3a):

a. The difficulty of obtaining an accurate model of the system to be controlled – the entire Spanish PV sector – that could be used for designing and validating any potential control policy.
b. The destabilizing effect of the delays associated to the implementation and putting into service of GCPVS[8]. These delays increase the sensitivity of closed-loop systems to the control action, even causing an unstable system response [26].
c. The particular initial conditions under which the control block should begin to operate. It had to stabilize an overreacted system output, with the additional pressure of an important number of facilities that expectedly would fail to benefit from the extinguishing framework and would be queuing up to enter in the incoming.

Hence, the new control structure was built on the concept of saturation[9], a simple and robust mechanism able to cope with the aforementioned uncertainties and obstacles. In essence, a saturation block in a control system imposes upper and lower limits on its input signal, so that the output will be bounded between pre-defined levels, even in the presence of an unstable input [32] (Fig. 3b).

This saturation action has its counterpart in a specific stage of the administrative procedure for the authorization of GCPVS, namely, the Pre-Allocation Register (RPA), where all the new PV facilities need to be registered for the assignment of their corresponding *FIT*[10].

Every GCPVS typology[11] k is assigned at the beginning of a year i a certain base power target ($Pb_{(k,i)}$), which is equally distributed into N annual power calls ($Cp_{(k,i,n)}$)[12] that are the set-points consecutively applied to the control scheme.

$$Cp_{(k,i,n)} = \frac{Pb_{(k,i)}}{N},\ 1 \le n \le N \tag{1}$$

The PV sector responds to $Cp_{(k,i,n)}$ by investing in a certain amount of PV power ($P_{\text{inv }(k,i,n)}$). But, by way of a saturation action,

[8] As stated in [31], the construction of electric power plants is a process with inherent delays, which hinder the task of building exactly the right number of plants to supply a rapidly changing demand and cause long oscillations between overcapacity and undercapacity.

[9] Saturation is addressed via caps capacity, to which this paper refers from here on.

[10] RD 1578/2008, articles 4–10, Annex III, Annex IV.

[11] Article 3 of RD 1578/2008 establishes two GCPVS typologies, namely, Type I (on-roof facilities) and Type II (other facilities). Additionally, Type I is subdivided into Type I.1 (rated power up to 20 kW) and Type I.2 (rated power exceeding 20 kW).

[12] Annex III of RD 1578/2008 sets to 4 the number of annual calls ($N=4$).

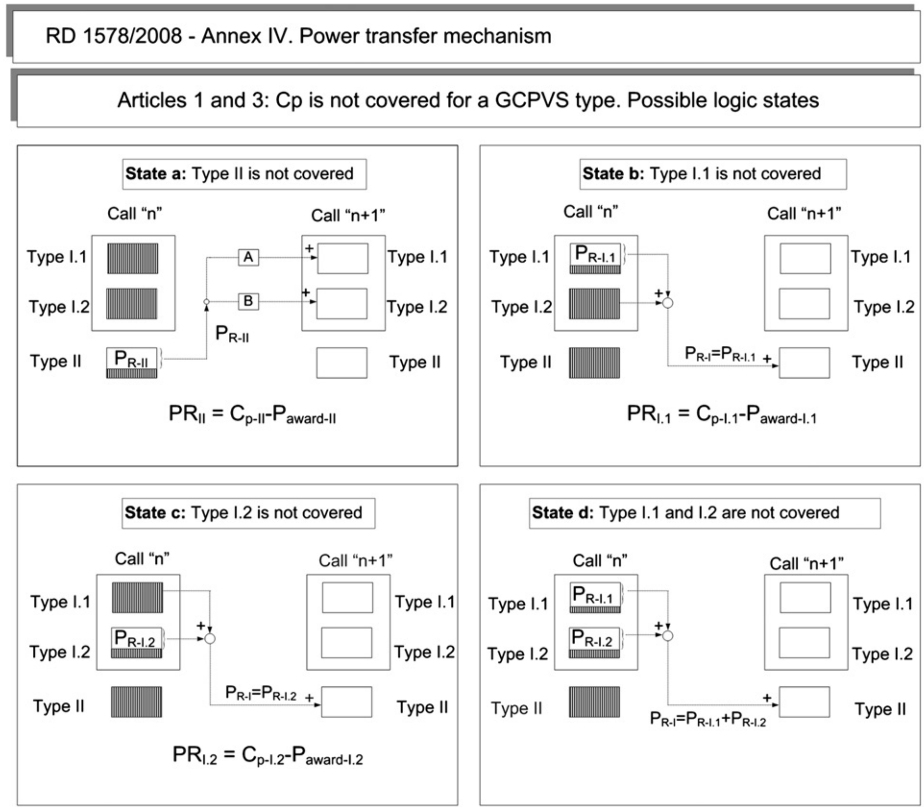


Fig. 4. Power transfer mechanism when *Cp* is not covered for a GCPVS type. *Source*: self elaboration based on [19].

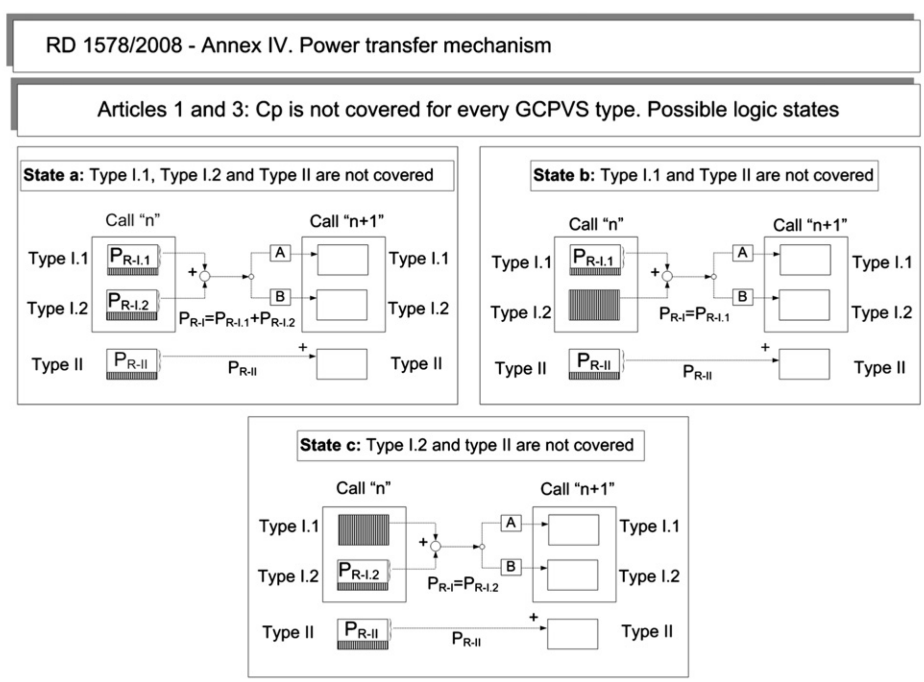


Fig. 5. Power transfer mechanism when *Cp* is not covered for every GCPVS type. *Source*: self elaboration based on [19].

the PV power finally awarded for registration in the RPA ($P_{\text{award }(k,i,n)}$) is not allowed to exceed $Cp_{(k,i,n)}$.

$$Pinv_{(k,i,n)} \leq Cp_{(k,i,n)} \;\Rightarrow Paward_{(k,i,n)} \;=\; Pinv_{(k,i,n)} \quad (2.a)$$

$$Pinv_{(k,i,n)} > Cp_{(k,i,n)} \;\Rightarrow Paward_{(k,i,n)} \;=\; Cp_{(k,i,n)} \quad (2.b)$$

Thereby, the limited enrolment capacity of the RPA exerts a saturation effect on ($P_{\text{award}(k,i,n)}$), which after a delay, will become installed power ($P_{\text{installed }(k,i,n)}$).

On the other hand, it was established a power transfer mechanism by which, in the event that a particular PV typology – either on-roof or on-floor – fell below its target, the power quota not covered would be transferred in the next call to the

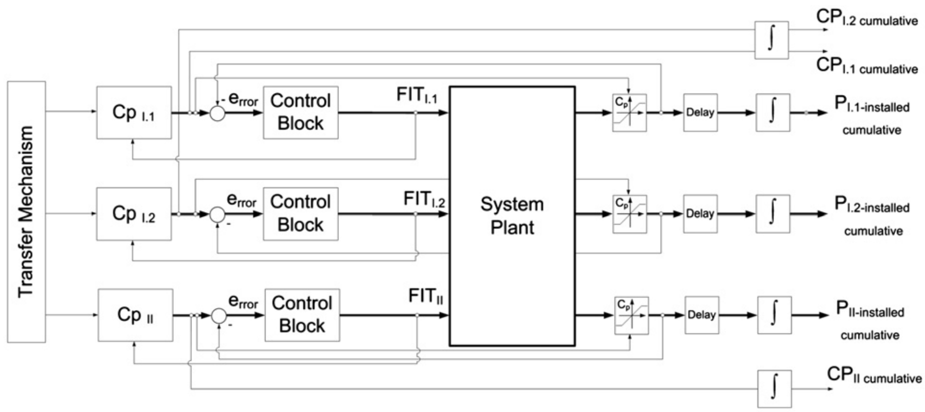


Fig. 6. Simplified MIMO control system structure applied. *Source*: self elaboration.

other PV typology that did reach its goal. In case that all PV typologies failed to reach their set-points, each of them would accumulate for the next call their remaining power quotas (Figs. 4 and 5).

3.2. Other features of the new energy policy control

3.2.1. Multiple input multiple output (MIMO) control structure and GCPVS on roof promotion

The lack of surveillance of the on-roof GCPVS promotion contributed to the low implantation of this PVS typology. Thus, the former single input single output (SISO) control structure became a MIMO scheme, which introduced separate set-points and control loops for each type of GCPVS (Fig. 6).

Giving additional support to on-roof GCPVS, the initial power target assigned to this kind of facilities doubled that for the on-floor typology[13].

Also, the new MIMO control scheme assigned particular *FIT*s for each of the GCPVS typologies[14]. This prevented a facility to benefit from undue higher *FIT* values. Additionally, the possibility of segmenting an on-roof PV facility was excluded by not recognizing – for remuneration purposes – as single PV facilities those located on the same parcel. Instead, the aggregated production capacity would be used to determine the *FIT* to apply[15].

3.2.2. The set point mechanism and the economic investment guarantee

An objective of the new regulatory framework was limiting the economic impact on the electricity sector of the future PV facilities. At the same time, there was also the aim to continue PV investments. To satisfy both requirements, the new mechanism linked the annual power target of each GCPVS type to the decrease experienced by its *FIT*.

Specifically, for a GCPVS type k, the new base power target ($Pb_{(k,i)}$) for the year i is updated as a function of the base power target of the previous year ($i-1$) and the cumulative rate of *FIT* ($FIT_{(k,i-1)}$) variation experienced during the year ($i-1$) according to[16,17] :

$$Pb_{(k,i)} = Pb_{(k,i-1)} \times \left(1 - \sum_{n=1}^{N} \frac{\Delta FIT_{(k,i-1,n)}}{FIT_{(k,i-1,n)}}\right) \forall i \geq 1, \quad N=4 \tag{3}$$

In other words, an increase in the base power target was conditioned to a previous decrease in the *FIT*, ensuring in this way the economic sustainability of GCPVS promotion.

Another advantage of this mechanism is the flexibility it allows in setting the power goals for each period. Considering the allowable margin of variation for *FIT*s[18], the increase of new installed capacity for the period 2009–2020 would range between 2700 MW and 4700 MW[19]. Thus, the power set-point applied to the system would vary accordingly to the system evolution, adapting to the different possible scenarios[20]. This adaptive set-point mechanism is reflected in Fig. 7.

3.2.3. The input adjusting mechanism

The decoupling of the *FIT* and the degree of accomplishment of the power objectives was corrected by introducing a control law that links the *FIT* to the evolution of GCPVS implementation and adjusts it to reduce the error.

Thus, within a power call ($Cp_{(k,i,n)}$) the three possible control actions envisaged by this mechanism are:

1) Degressive control action by reducing the applied *FIT*:

$$\text{If } P_{\text{Award}\ (k,i,\ n-1)} \geq 0.75 \times Cp_{(k,i,\ n-1)} \tag{4}$$

$$\text{then } FIT_{(k,i,\ n)} = FIT_{(k,i,\ n-1)} \times \left[(1-K) \times \frac{Cp_{(k,i,n-1)} - P_{\text{Award}\ (k,i,\ n-1)}}{0.25 \times Cp_{(k,i,n-1)}} + K\right] \tag{5}$$

where

$$K = 0.9^{1/N} = 0.9^{1/4} = 0.9740 \tag{6}$$

[13] The power allocated in 2008 to Type I facilities was 267 MW (10% to subtype I.1 and 90% to subtype I.2) and 133 MW for Type II. Nevertheless, during 2009 and 2010, two extra power blocks (100 MW and 60 MW) were introduced for Type II facilities.

[14] The initial values of the FITs were established in 34 c€/kW h for installations of type I.1 and 32 c€/kW h for the other types.

[15] RD 1578/2008, article 10.

[16] RD 1578/2008, article 5.

[17] In Eq. (3) the values for ($Pb_{(k,0)}$) are declared at footnote 13.

[18] See Section 3.2.3.

[19] This would entail a total cumulative power for 2020 between 6000 MW and 8000 MW. In the best case, these objectives – when compared to those set by the different European National Renewable Energy Action Plans (NREAPs) – would be among the most ambitious in Europe, behind Germany [1].

[20] Upon entry into force of RD 1578/2008, power goals for 2020 were quite uncertain. Figures shuffled from 8367 MW (Spanish Renewable Energy Action Plan 2011–2020, PANER [33]) to 6735 MW (Congressional Subcommittee on Energy) and finally to 7250 MW (Renewable Energy Plan 2011–2020, PER [34]).

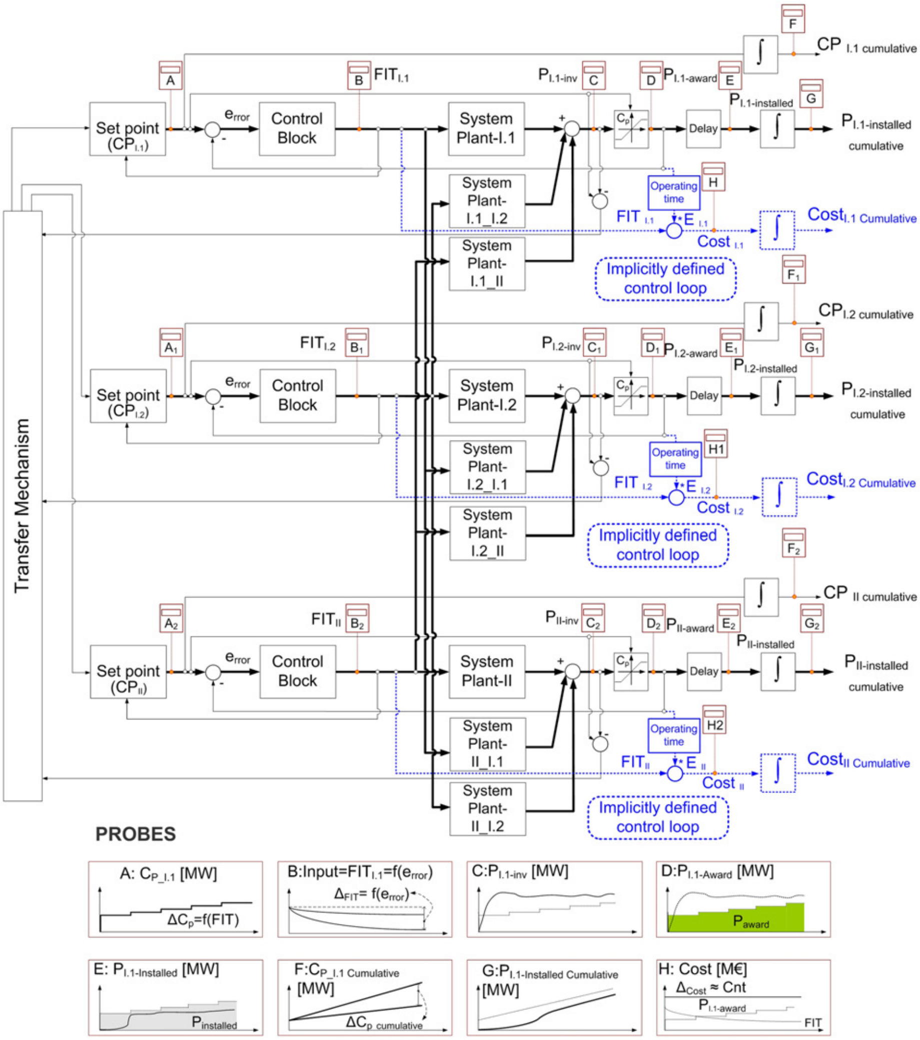


Fig. 7. Detailed MIMO control system structure applied. *Source*: self elaboration.

2) Invariant control action by keeping constant the applied *FIT*:

$$\text{If } P_{\text{Award }(k,i,n-1)} < 0.75 \times Cp_{(k,i,n-1)} \quad (7)$$

$$\text{then } FIT_{(k,i,\ n)} = FIT_{(k,i,\ n-1)} \quad (8)$$

3) Incremental control action by increasing the applied *FIT*:

$$\text{If } P_{\text{Award }(k,i,\ n-2)} < 0.5 \times Cp_{(k,i,\ n-2)} \quad \text{and} \quad P_{\text{Award }(k,i,\ n-1)} < 0.5 \times Cp_{(k,i,\ n-1)} \quad (9)$$

$$\text{then } FIT_{(k,i,\ n)} = FIT_{(k,i,\ n-1)} \times [1+(1-K)] \quad (10)$$

The structure of this algorithm naturally imposes upper and lower limits to the values taken by the *FIT*. Specifically, in the most likely scenario of full coverage of all the power calls, a *FIT* annual decline of approximately 10% is obtained.

Fig. 7 illustrates the mechanisms introduced by the new regulatory framework in terms of MIMO control systems and shows the higher degree of complexity introduced in comparison to the former (Fig. 2b). The same control scheme includes several probes (for a fixed typology) aimed at illustrating the evolution of system variables as a function of the control actions applied.

4. The new control structure and the system response

4.1. The output stability and the promotion of GCPVS on roof

Data on the new control scheme have been collected from different government sources (CNE, Ministry of Industry, etc.) and have been illustrated in Fig. 8. Next, signal probes are placed in a simplified representation of the new control structure and for each of the PV types the monitored magnitudes are displayed in separate graphs (Fig. 8).

Signal probes labeled "A", "C" and "D" capture the set-point Cp, the plant output P_{inv} and the output of the saturator block (P_{award}), respectively. This information is displayed together on the graph entitled "Saturation mechanism results (probes A, C and D)", where the Cp level is represented by a dashed line and P_{inv} by a bar. Additionally, P_{inv} is decomposed into segments which are proportional to P_{award}, to the PV power admitted for registration in the RPA but still not awarded[21] and to the PV power not admitted for registration in the RPA[22]. Signal probe "B" captures the plant input *FIT*, and it is displayed on the graph entitled "Inputs (probe B)". Signal probes "F" and "G" capture the

[21] In the case of full coverage of C_p, admitted but still not awarded applications remain on the waiting list for the next call, unless expressly stated otherwise by the applicant.

[22] The case of applications with formal defects.

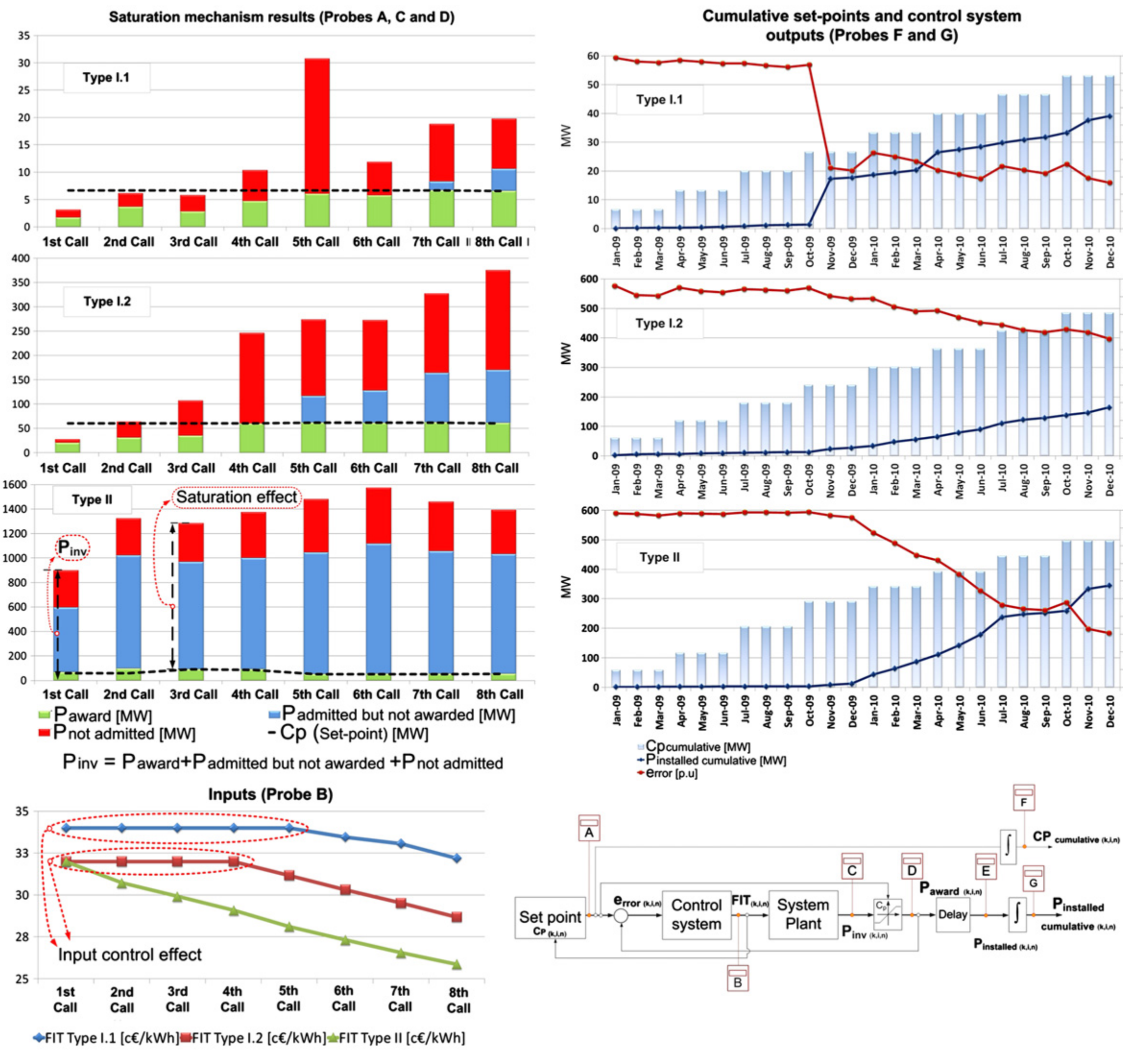


Fig. 8. Control system evolution in the period 2008–2010. *Source*: self elaboration based on CNE and Ministry of Industry data.

cumulative values of the set-point ($Cp_{\text{cumulative}}$) and the output of the closed-loop control system ($P_{\text{installed cumulative}}$). This information is displayed together on the graph entitled "Cumulative set-points and control system outputs (probes F and G)".

Fig. 8 shows that at the end 2010, Cp would have been overcome by P_{inv} in approximately 314 MW for type I.2 and 1.340 MW for type II, respectively (probes A, C and D)[23]. Hence, the saturating effect of the RPA is an effective mechanism to ensure the predictibility and stability of the system's response.

The savings achieved are given by the product of the power of the new applications not included in the RPA within each call by the annual operation time[24] and the *FIT* of the particular call. It can be estimated that 125–171 M€ for Type I.2 and 615–842 M€ for Type II have been saved for the Spanish electricity system, i.e., over 1.013 M€ per year over the next 25 years[25].

In view of the results obtained in terms of stability, the Royal Decree Law (RDL) 6/2009 [35] extended this mechanism prevent that the runaway evolution of GCPVS could occur again in other RES-E sectors such as wind and thermosolar.

In addition to the new specific framework for on-roof GCPVS promotion, the saturation mechanism may have also contributed to the reorientation of Spanish PV sector towards on-roof facilities, as it has made impractical to install new on ground facilities in the short term[26] (Fig. 8, probes A, C and D). While on-roof facilities meant less than 10% of total GCPVS in the period 1998–2008 they achieved up to 40% (200 MW) at the end of the period 2008–2010 (Fig. 8, probes F and G). It is worth noting that the achievement of the power objectives set for Type I GCPVS was improving gradually until attaining the full coverage of the calls from 2010.

[23] The high initial conditions of the variable P_{inv} for Type II GCPVS – about 900 MW in the first call and above the 1200 MW from the second call – exceeded by far the limits set in the new regulatory framework. All this despite the additional power quota introduced in the years 2009 and 2010 for these facilities and the transfer of power received from the Type I for not covering its objectives during the first four calls. Although the evolution of P_{inv} for Type I.2 was different, from the fourth call it exceeded the 200 MW.

[24] The operation time is the time during which GCPVS produce energy. Otherwise stated, it is referred to annual periods and is measured in hours. In 2008, the operation time of GCPVS in Spain was 1284 h, while in 2009 it was 1755 h.

[25] It is the temporary effect of the retribution economic framework of RD1578/2008.

[26] The waiting period from application for registration in the RPA to obtain final registration, i.e., since P_{inv} becomes P_{award}, is over two years.

4.2. The economic stability: Control deficiencies and their correction

The RD 1578/2008 is not explicitly aimed at GCPVS cost containment and does not regulate this matter expressly. However, it poses an implicit control loop intended to limit the GCPVS impact on the economic stability of the Spanish electricity system (see Figs. 3b and 7) by adjusting the base power target as a function of the *FIT* (Section 3.2.2), offsetting the increase in power objectives with the reduction of their remuneration. This section is aimed to analyze the performance of this implicit mechanism for cost containment.

For every GCPVS type *k*, given a quarterly call *n* within a year *i*, the cost ($Cost_{(k,i,n)}$) associated to this period is given by the product of the generated energy ($E_{(k,i,n)}$) and the ($FIT_{(k,i,n)}$). However, the implicit cost containment mechanism approximated ($E_{(k,i,n)}$) as the product of $P_{\text{award }(k,i,n)}$ and the operating time ($T_{(k,i,n)}$) (Figs. 3b and 7).

$$Cost_{(k,i,n)} = E_{(k,i,n)} \times FIT_{(k,i,n)} \cong P_{\text{award }(k,i,n)} \times T_{(k,i,n)} \times FIT_{(k,i,n)} \quad (11)$$

To illustrate the cost conservation effect, the most likely scenario of full coverage of all the quarterly calls will be taken as a reference:

$$C_{P(k,i,\ n)} - P_{\text{award }(k,i,\ n)} = 0 \quad (12)$$

This entails a maximum *FIT* annual reduction of approximately 10%:

$$\sum_{n=1}^{4} \frac{\Delta FIT_{(k,i,n\ )}}{FIT_{(k,i,n\ )}} = -10\% \quad (13)$$

Which implies:

$$P_{b(k,i+1)} = 1.1 \times P_{b(k,i)} \Rightarrow C_{P(k,i+1,n)} = 1.1 \times C_{P(k,i+1,n)} \quad (14)$$

$$FIT_{(k,i,n\ )} = 1.1 \times FIT_{(k,i+1,n\ )} \quad (15)$$

$$P_{\text{award }(k,i,n)} = C_{P(k,i,n)} \Rightarrow E_{(k,i,\ \ n)} = C_{P(k,i,n)} \times T_{(k,i,\ \ n)} \quad (16)$$

The cost ($Cost_{(k,i)}$) associated to the year *i* is:

$$Cost_{(k,i\ )} = \sum_{n=1}^{4} FIT_{(k,i,n\ )} \times C_{P(k,i,n\ )} \times T_{(k,i,n)} \quad (17)$$

Likewise the cost ($Cost_{(k,i+1)}$) for the year $i+1$ will be:

$$Cost_{(k,i+1\ )} = \sum_{n=1}^{4} FIT_{(k,i+1,n\ )} \times C_{P(k,i+1,n)} \times T_{(k,i+1,n)} = \sum_{n=1}^{4} FIT_{(k,i,n\ )} \times C_{(k,i,n)P} \times T_{(k,i+1,n)} \quad (18)$$

then:

$$T_{(k,i+1,n)} = T_{(k,i,n)} \forall (k,i,n) \Rightarrow Cost_{(k,i+1)} = Cost_{(k,i)} \quad (19)$$

In particular:

$$T_{(k,i,n)} = \text{constant } \forall k,i,n \Rightarrow Cost_{(k,i\ )} = \text{constant}' \forall k,i \quad (20)$$

Thus, the cost remains constant through time provided that the operation time is also constant.

This was a reasonable hypothesis according to the data of the period 1998–2008, but it has proved to be misleading in view of the particular design of the implicit cost containment mechanism. The results of the period 2009–2010 revealed an increase in the production capacity[27] that could not be limited because $E_{(k,i,n)}$ was not a controlled variable. Instead, this energy production growth was accounted as a virtual rise of the operation time, which was not subject to control on the premise of being constant (Fig. 9).

Taking as reference the 2008 operation time[28], the cost of P_{award} along the period 2009–2010 for all GCPVS types (Fig. 8, probes A, C and D) would have amounted to approximately 377.3 M€ per year over the next 25 year. Nevertheless, with the 2009 virtually incremented operation time the cost finally amounted to 515.9 M€ per year, representing an increment over 138 € (36.8%).

The amendment to this inefficient cost control scheme took place towards the end 2010 via two main changes in the control of the promotion policy:

- RD 1565/2010 [44]. This decree imposed a drastic reduction of the *FIT*s applied to GCPVS covered by the RD1578/2008. Hence, the *FIT*s corresponding to Type I.1, Type I.2 and Type II experienced an extraordinary reduction of 5%, 25% and 45%, respectively[29] (Fig. 10). This measure represented an annual saving of around 140 M€ and counteracted the cost increment of approximately 138 M€ per year provoked by the experienced increase in production capacity.
- RDL14/2010 [45]. This decree limited the operating time eligible for premium of GCPVS covered by the RD 1578/2008[30]. This action has prevented the consolidation of the experimented increase in production capacity and thereby, future cost deviations. However, it can limit the development of more efficient PV technologies, because it discourages improvements in efficiency as a path to increased revenue.

This shows that capacity caps policies may not fully guarantee the cost stability, unless the control loop is properly designed. Furthermore, the changes introduced to minimize the cost could be technically inappropriate; limiting the operating time of new GCPVS may discourage from increasing energy production and/or improving efficiency. However, relaxing this constraint should be accompanied by further control measures aimed at preventing the opportunistic repowering of existing GCPVS.

4.3. The promotion of investments in PV technology

The power ser-point mechanism introduced has effectively contributed to the continuity of GCPVS promotion and approximately 1000 MW cumulative power target was set for the period under study. Nevertheless, this positive effect was offset by a slowdown in installed capacity of approximately one year, from October 2008 until practically November 2009 (see Figs. 8 and 10). A determining factor in this break was the introduction in the control scheme of the saturation block–the RPA[31] – at the output of the plant[32]. Actions aimed at preventing booms and busts

[27] Delay and experience may be undelaying factors of this growth. In 2009 came into operation most of the new 2500 MW installed in 2008. Possibly, thin-film modules, which presented higher production during the early years, could have been employed. Gained experience could also have contributed to better PV plants operation [36]. Furthermore, there is the repowering of GCPVS covered by the RD 661/2007 – driven by the large reduction in the cost of PV panels and the

(*footnote continued*)
legal flexibility towards this practice [36–39] – which increments energy production by increasing the photovoltaic field [40–43].

[28] See footnote 24.

[29] In fact, the RD 1578/2008 (Fifth Additional Provision) allows the revision of the *FIT*s in 2012, in view of the technology and the market development, and the performance of the remuneration framework.

[30] It is noteworthy that a substantial part of the corrective actions formulated in [44,45] were made retroactive, affecting the facilities covered by the former RD 661/2007 [15,28].

[31] Remarkably, the quarterly calls limits were systematically violated in the eight calls of the period 2009–2010, with the generation of the consequent delays.

[32] Other causes of the installed power slowdown pointed from the PV sector are the voluntary delay in the acquisition of equipment of some industry players for benefiting from the progressive reduction in the prices or the difficulties in financing due to the tightening of credit conditions.

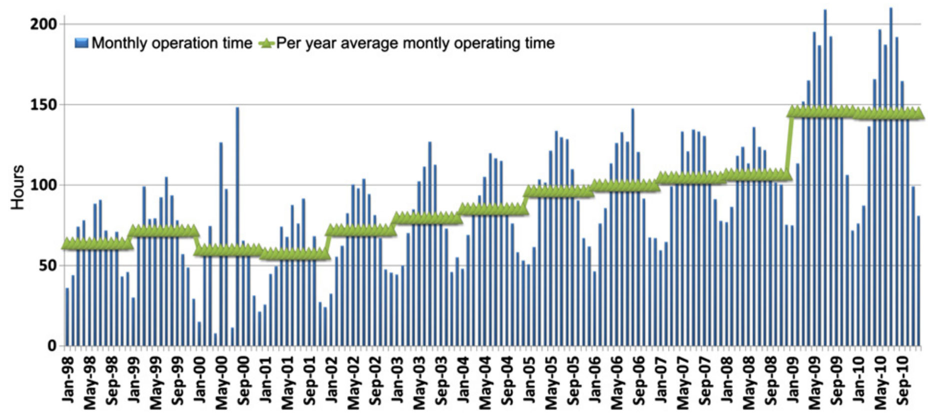


Fig. 9. Operation time evolution in the period 1998–2010. *Source*: self elaboration based on CNE data.

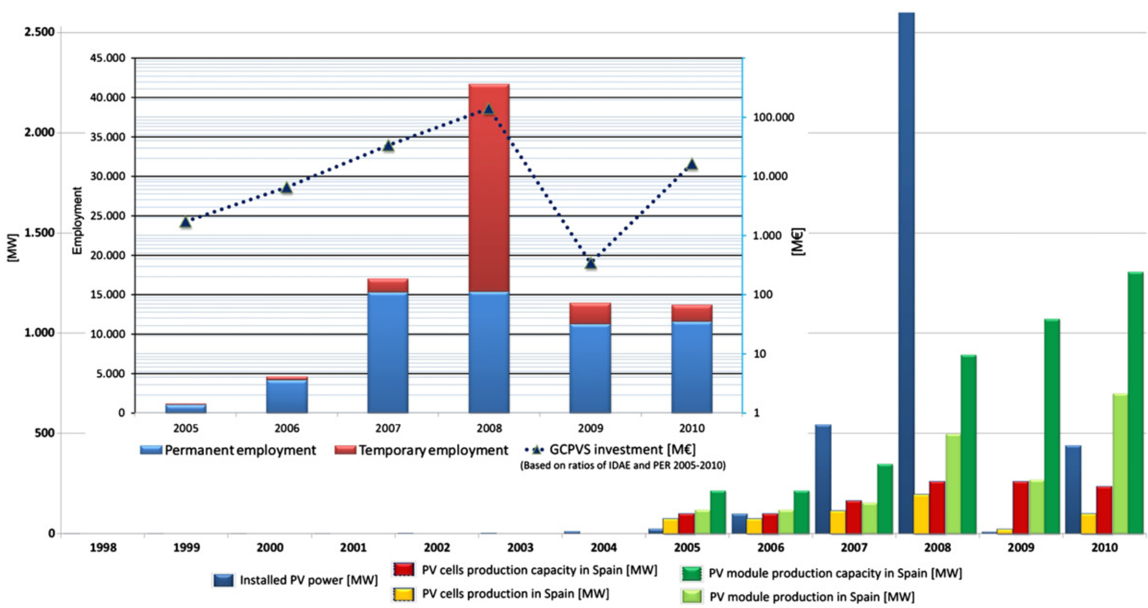


Fig. 10. Spanish PV sector evolution in the period 1998–2010. *Source*: self elaboration based on CNE, IDAE and ASIF data.

cycles have increased administrative complexity and cueing procedures, which undermine GCPVS investments[33].

The Spanish PV sector hypertrophy [26,28] magnified the natural consequences of the break in the installed power of 2009, leading to a significant reduction in GCPVS investment and a noticeable loss of jobs. However, the loss mainly affected temporary contracts, leaving occupation levels of the Spanish PV industry above those obtained in 2006, despite the slowdown caused by the new regulatory framework and the international crisis[34] (Fig. 10). This slowdown also had a significant impact outside Spain. The Spanish contraction "*has upset the global PV market* [...] *and has sent shock waves across the global value chain*" [46].

Compared to the initial conditions set by the former RD 661/2007, RD 1578/2008 reduced *FIT* by 22.7% for Type I.1 and 27.3% for Types I.2 and II, respectively (see Fig. 11). These initial *FIT* reductions, and the subsequent, favored the fulfillment of another objective, namely, reducing the installation cost of GCPVS (also in Fig. 11)

Additionally, by the effect of the corrective RD 1565/2010, the accumulated *FIT*s reductions reached 32.3% for Type I.1 GCPVS, 52.5% for Type I.2 and 68,8% for Type II, respectively, regarding the conditions set by RD 661/2007. Furthermore:

- The requirements that an on-roof GCPVS must meet to be classified as a Type I facility – and benefit from a higher *FIT*, if applicable – have become more restrictive.
- The mechanism of RD 1578/2008 for the reinstatement to the power targets of the power awarded, but not executed, has been removed. This power is now simply lost.
- The extraordinary *FIT* reductions applied have not been accompanied by increases in power objectives in the terms established by RD 1578/2008.

4.4. Final remarks beyond the period 2008–2010

The latest reforms of the Spanish PV sector, especially the RDL 14/2010, are a sign of the concern on the economic impact of the

[33] From the PV sector it is also accused of eliminating competition, promoting the sale of permits and damaging the industry and the employment.

[34] The sector aims at the international presence that kept the Spanish PV industry during the period 2009–2010 as one of the factors that prevented a further decline in employment. In particular, in 2010 almost 66% of module and solar trackers and 86% of the inverters production went to export [36,47].

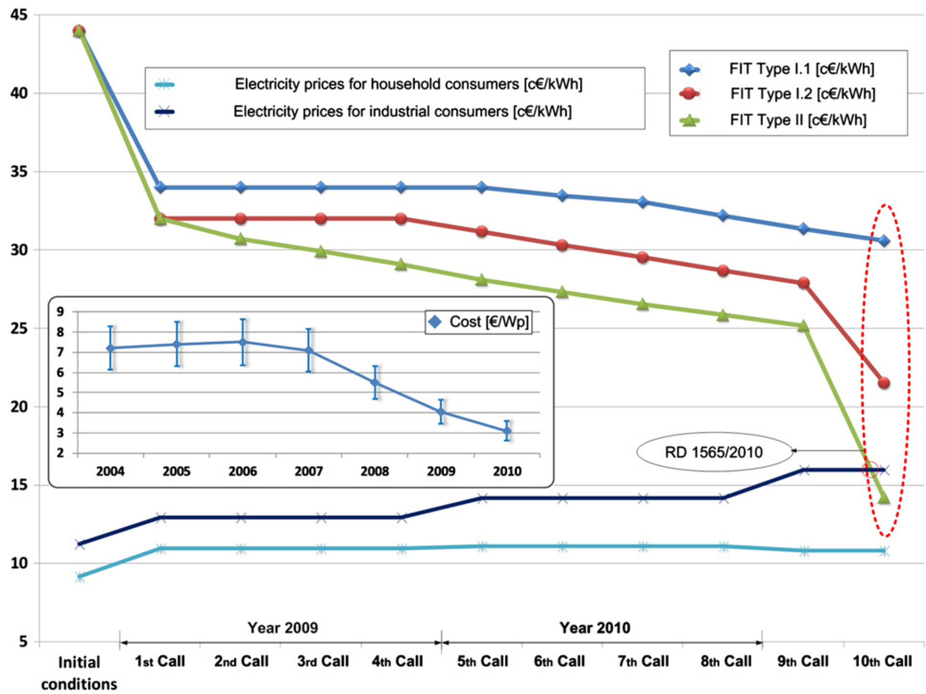


Fig. 11. Price evolution in the period 2008–2010. *Source*: self elaboration based on companies from the PV sector, CNE, Ministry of Industry, and EUROSTAT data.

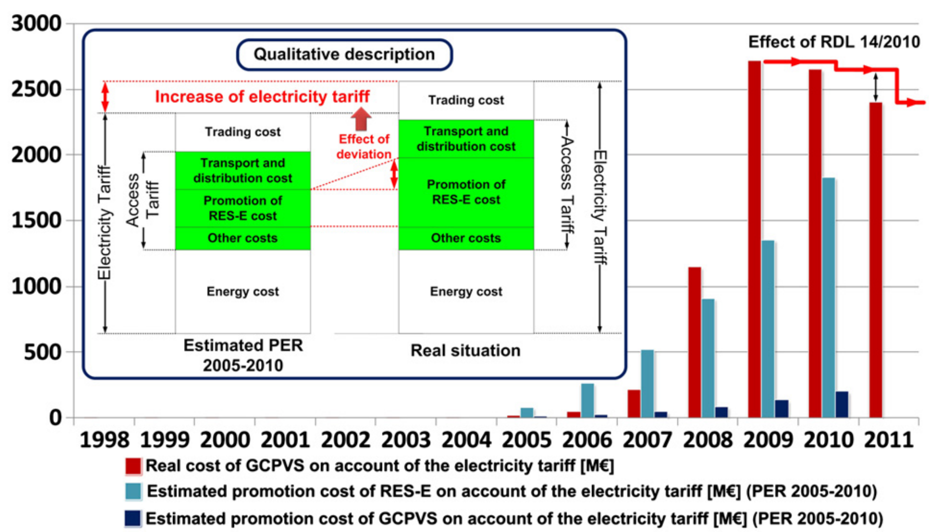


Fig. 12. Cost evolution and its impact in the electricity tariff. *Source*: self elaboration based on CNE and IDAE data.

promotion of GCPVS in the Spanish Electricity Sector (SES). As previously indicated, the RDL 14/2010 affected the economic control structure of RD 1578/2008 but also the economic regime of all GCPVS installed before October 2008. The main elements of the Royal Decree Law 14/2010 can be summarized as follows:

- Introduction of a toll to access to the grid (0.5 €/MW h).
- Introduction of limits reducing the operating time eligible for premium of GCPVS covered by the former regime and the RD 1578/2008. These limits are function of the climatic zones defined in the RD 314/2006. Exceptionally, GCPVS belonging to the former regime – RD 661/2007 – will have more restrictive limits until 2013.

The promotion cumulative cost of GCPVS was expected to be less than 499.4 M€ at the end of the period 2005–2010 [48]. However, at the end of 2010, this cost was, at least, 6802.8 M€ (see Fig. 12), which increased the Spanish power tariff deficit [49] and, consequently, the electricity tariff charged to consumers[35]. Fig. 12 incorporates extra cost data from 2011; these new data confirms the decreasing trend introduced by RDL 14/2010.

Although RDL 14/2010 has succeeded in restricting the impact on the tariff deficit, the urgent need to reduce the Spanish power tariff deficit has forced the Government to enact the very recent RDL 1/2012 [50], which repealed economic incentives for all new RES-E facilities fourteen years after the beginning of RES-E promotion. Still, the main problem of regulating the Spanish PV

[35] The impact of the PV cost in the electricity tariff is given by the trading cost, the energy cost and the access tariff. The cost of RES-E – included the PV cost – is charged on the access tariff.

industry is how to deal with the overflowed cost[36] caused by the control deficiencies of the previous legal frameworks.

The economic volatility and the retroactive corrections have introduced elements of evident risk [51–53]. The drastic measures adopted has led to a process of judicialization of the Spanish PV sector[37], which further stimulate the perception of legal uncertainty and reduces credibility and confidence not only in the Spanish renewable energy sector but in the opportunities for foreign investments.

5. Conclusions

This paper has collected and presented data describing the evolution of GCPVS in Spain for the period 2008–2010 after the so called Spanish PV Boom.

The regulatory framework governing GCPVS in Spain since 2008 has been examined from a feedback control systems approach, translating its legal structure into an equivalent control scheme. Tending this parallelism has allowed to apply basic control principles to discern the mechanisms behind the significant changes occurred in this period and to assess the effectiveness and efficiency of the control actions introduced.

One of the most obvious changes was the transformation of the former SISO control scheme into a MIMO structure. This allowed establishing separate set-points and control loops for an efficient monitoring of the implantation of the different GCPVS typologies (on-floor and on-roof). A goal successfully achieved in this sense was the reorientation of the Spanish PV sector towards GCPVS on roof, belonging almost 40% of the new installed power to this typology.

Another relevant change was the introduction of a control law for the *FIT* that was linked to the evolution of the GCPVS implementation, allowing both the increase and the decrease of the *FIT*, as necessary to reduce the error. This reported to the system all the benefits of feedback loops, putting an end to the former open-loop operation.

The new control structure was built on the concept of saturation. Specifically, an implicit control loop intended to contain the economic cost of the system was implemented, which was based on the saturation of the plant output – the installed PV power – and on the decrease of the plant input – the *FIT* –. However, although the strong saturating action applied certainly curbed the unbridled system's response, it also caused a slowdown in installed capacity of approximately one year, leading to a significant reduction in GCPVS investment, a noticeable loss of jobs, and turning to employment levels near those of 2006.

The new control framework has proved to be robust and to produce the reduction of the unit cost of GCPVS. However, the indirect approach given to the cost control problem proved ineffective in preventing the economic impact of the production capacity growth occurred in 2009. This mechanism increased the cost of the electricity system and, together with the tariff deficit, led to the adoption of aggressive and retroactive actions which severely questioned the trustability of future investments in the Spanish renewable energy sector. The main issue is shown to be the management of the cost problem generated within the previous legal frameworks.

Regarding methodology, the qualitative application of well-established control principles has shown to be a useful tool for the analysis and assessment of the regulatory changes occurred in the Spanish PV sector. Furthermore, it can be expected to be able to be easily adapted to other sectors and countries.

[36] However, the debate about the cost and fitness of PV generation is not unique to Spain; Germany has also produced critical analysis in relation to the cost of promoting this technology [21].

[37] In the case of GCPVS under RD 1578/2008, the causes of disputes mainly relate to the limitation of operating time eligible for payment of the premium.

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